**USARIEM TECHNICAL NOTE TN03-3**

# LOAD CARRIAGE MODEL DEVELOPMENT AND TESTING WITH FIELD DATA

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The results of a field study of the energy costs of downhill walking and load carriage were used to test a modification of the Pandolf equation (PE) for the prediction of downhill load carriage energy costs. PE is a predictive equation for the energy cost of walking and load carriage on level and uphill terrain. The field study objective was to broaden the database to include slower walking speeds. A new dataset was collected in the field with loads of 0 kg and 27.2 kg at speeds of 0.89 m×s-1 and 1.12 m×s-1 on grades of 0%, -4%, -8.6% and -10.2%. Oxygen uptake was collected using portable oxygen monitors. To adjust the PE for downhill movement, a correction factor (CF) was derived using data from a prior laboratory study. The final equation is CF = h×[(G×(W+L)×V)/3.5 - ((W+L)×(G+6)2)/W) + (25-V2)]. The adjusted values, using the M = PE - CF format, fit well for walking at 1.12 m·s-1, but at 0.89 m·s-1, values were underestimated. Thus, an adjusted PE derived from a laboratory study for walking, and load carriage was valid at 1.12 m·s-1 for loads up to 27 kg, but was not acceptable at 0.89 m·s-1.

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## BACKGROUND

The development of predictive models is an assigned mission of USARIEM under STO3U. This study was in response to a specific need for input into models being developed by USARIEM and for cooperative projects with other organizations such as the IUSS being developed by the U.S. Army Soldier Biological and Chemical Command (SBCCOM). The data collected during 2001 were used to evaluate a model developed from data collected during 1998. The telemetry temperature pill and activity monitor are prototype components of the Warfighter Physiological Status Monitor (WPSM). This study also presented an opportunity to expand the performance database for these sensors during controlled field use.

## ACKNOWLEDGMENTS

The authors would like to thank the following individuals for their assistance in preparing this technical report: the Commander and the staff of Yakima Training Center, Ms. Diane Danielski, and our 8 test subjects.

## EXECUTIVE SUMMARY

This paper describes a field study of the energy costs of downhill walking and load carriage, the derivation of a modification of the Pandolf (6) equation (PE) for the prediction of downhill load carriage energy costs, and the use of the field data to test the new adjusted Pandolf equation.

The objective of this field study was to broaden the field database to include slower walking speeds. Field testing was conducted at Yakima Training Center (YTC). To meet those goals and to obtain additional field data, a new dataset was collected in the field with pack loads of 0 kg and 27.2 kg at slower walking speeds of 0.89 $m{\cdot}s^{-1}$ and 1.12 $m{\cdot}s^{-1}$, on level and downhill grades of 0%, 4%, 8.6% and 10.2%. Slopes were of sufficient length to obtain steady state values for oxygen consumption (ml/kg/min) by allowing subjects to walk steadily for 15-20 min. Oxygen uptake was collected using portable oxygen monitors.

The PE is a predictive equation for the energy cost of walking and load carriage on level and uphill terrain. However, for walking on downhill slopes, the predicted decrease in energy costs is too great (7). To adjust the PE for downhill movement, a correction factor (CF) was derived from data collected during a prior laboratory study (8). The original data set was obtained for pack loads of 0 (no-load), 9.1 kg and 18.1 kg for 16 subjects walking on a treadmill at 1.34 $m{\cdot}s^{-1}$ (3 mph) on downhill grades of -12%, -10%, -8%, -6%, -4%,-2%, a level (0%) treadmill, and 4%, 8% and 12% uphill grades. An original set of equations was derived from that study (8) and was tested against field data (9) for pack loads of 0 kg, 13.6 kg, and 27.2 kg, all at a walking speed of 1.34 $m{\cdot}s^{-1}$. The new algorithm was validated using the field data for downhill, level, and some uphill grades, but there was some dissatisfaction with the field data. In addition, the original algorithm was derived and tested for only the 1.34 m·s-1 walking speed. Due to the questionable results with the new algorithm for uphill field data and the wide spread acceptance of the PE, the authors focused this study on developing a CF for downhill load carriage in the context of the PE. The final equation is $CF = \eta\cdot[(G\cdot(W+L)\cdot V)/3.5 - ((W+L)\cdot(G+6)^2)/W) + (25-V^2)]$. The adjusted values, using the M = PE - CF format, fit well for walking at 1.12 $m{\cdot}s^{-1}$, but at 0.89 $m{\cdot}s^{-1}$, values were underestimated. Thus, an adjusted PE derived from a laboratory study for walking, and load carriage was valid at 1.12 $m{\cdot}s^{-1}$ for loads up to 27 kg, but was not acceptable at 0.89 $m{\cdot}s^{-1}$.

## INTRODUCTION

### PURPOSE

This paper reports on a continuing research program to quantify the metabolic cost of load carriage. The paper describes a field study that expands our database for energy expenditure during walking and load carriage over uphill, level (0-grade), and downhill slopes. The primary data collected during the field study was the volume of oxygen ($VO_2$) consumed. The paper also describes the derivation of a correction factor (CF) for the Pandolf equation (PE) for downhill walking and load carriage. The CF was derived using data from a prior laboratory study (8). Data gathered from the present field study was then used to evaluate how well the energy cost of downhill walking was predicted when the new CF was used with the PE.

### MILITARY RELEVANCE

Metabolic costs are important to soldier performance, as soldiers have only limited energy reserves. An activity has a certain energy cost, and if energy reserves are insufficient, the soldier either may not be able to perform that task, or the level of performance may be reduced. Depletion of energy reserves may also contribute to fatigue. A second level of concern is thermal stress. As the body converts or metabolizes stored chemical energy into mechanical energy, if the heat generated is not lost by active or passive thermoregulation, body core temperature will increase.

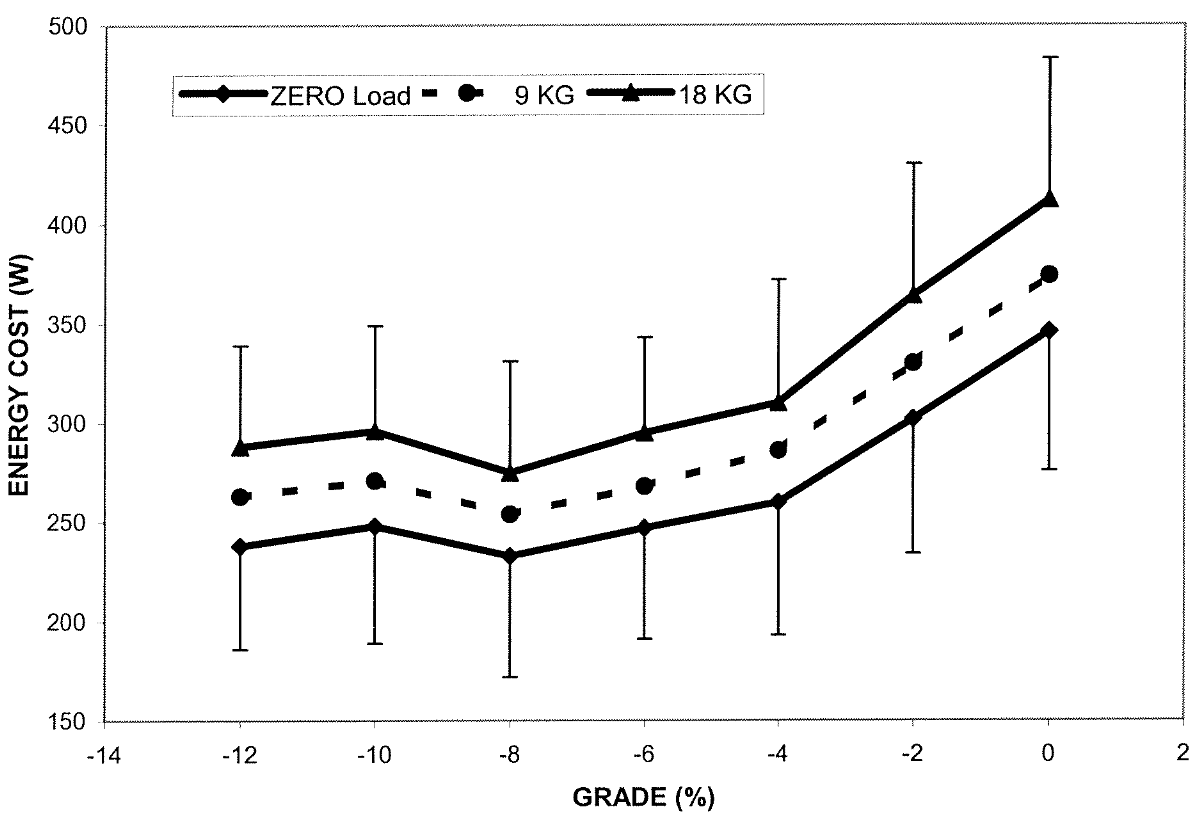
### GENERAL

While walking on a level grade at a constant speed, energy costs increase as the load increases, but because the load is only temporarily displaced in a vertical plane with no net change in vertical displacement, no external work is performed against gravity. When moving uphill on a constant slope at a given speed and time, there is a vertical lift, and work is performed against gravity. The load includes body mass. On a downhill or negative slope, gravity "pushes" the load downhill a vertical distance, performing work on the total mass (negative work), and thereby reducing the cost of load carriage relative to level load carriage. The cost of moving a load up or downhill on a slope is theoretically equivalent to a simple vertical lift or drop of the same height, but the efficiency or inefficiency varies to some degree with differences in slope and/or frictional forces. In downhill movement, negative work may result in acceleration of the individual as gravity exerts a downhill push until he/she loses control and falls. Instability during downhill movement occurs whenever forward momentum overcomes the resistance to acceleration or deflection provided by the total mass. Energy must be expended to maintain stability. The additional cost of maintaining stability by braking or other postural changes is the primary reason that the PE predicted values for downhill movement are too low.

### FIELD STUDY

The test protocol built upon our prior laboratory (8) and field (9) studies. The laboratory study consisted of downhill (-12%, -10%, -8%, -6%,-4%,-2%), level (0 grade), and uphill (+4%,+8%,+12%), with pack loads of 0 kg (no-load), 9.1 kg and 18.1 kg on a treadmill run at 1.34 $m{\cdot}s^{-1}$ (Figure 1). There were 16 subjects – 12 males and 6 females – in the laboratory study. The field test was conducted at YTC with pack loads of 0 kg, 13.6 kg, and 27.2 kg at a walking speed of 1.34 $m{\cdot}s^{-1}$. There were 8 male subjects in the 2000 field study. The test locations were a level, paved airstrip and gravel-surfaced roads and tracks with grades of 4%, 8.6%, and 12%. The field data sets were incomplete due to equipment problems, time constraints, and illness. Most downhill test runs were completed with all 8 male subjects, but uphill data collection was limited. Safety limits based on heart rate (HR), core temperature and Wet Bulb Globe Temperature (WBGT) were also set. For the 8.6% uphill test runs, only 2 of 8 subjects were able to complete the carry with the heaviest 27.2 kg load. It was apparent from that field study that the uphill pace of 1.34 $m{\cdot}s^{-1}$ was too fast. On the 12% downhill runs, there were also some concerns that the subjects would lose their balance and fall. An additional finding was that energy costs for the intermediate 9.1 kg load during the laboratory study were essentially equivalent to the average of the no load and 18.1 kg loads. The greater variability of the field data made it more difficult to make the same observation, but the same trend was present. Based on prior experiences, the new protocol was designed to eliminate some problems and to expand the database. For this study, relative to the first field study, the intermediate 13.6 kg load was eliminated, walking speeds were decreased, and a new oxygen monitor was employed. The subject population was also tested in groups of 4 over a 2-week period instead of testing 8 subjects over a single week.

Figure 1. Energy costs of treadmill load carriage at 1.34 $m{\cdot}s^{-1}$



## PANDOLF EQUATION (PE) CORRECTION FACTOR

PE (6) is a widely accepted (1) equation for predicting total energy consumption ($M_T = M_L + W_k$) during walking and uphill load carriage.

$$M_T = 1.5 \cdot W_{ND} + 2.0 \cdot (W_{ND} + L) \cdot (L/W_{ND})^2 + \eta \cdot (W_{ND} + L) \cdot (1.5 \cdot V^2 + 0.35 \cdot V \cdot G) \quad \text{(Equation 1)}$$

Subscripts were added to the original equation variables. The model variables are total energy costs ($M_T$) and the metabolic cost of level standing and walking ($M_L$) in watts, nude weight ($W_{ND}$), and load (L) in kg, walking speed (V) in $m \cdot s^{-1}$, and slope grade (G) as a percentage.

The equation can be logically broken down into elements for calculating the standing metabolic rate (SMR) for an individual of a certain weight, the additional cost of an external load (pack, etc.), and a cost for forward movement on the level. By convention energy costs that involve movement with no net vertical displacement are not "work". The final term in the equation uses slope grade to calculate a value for vertical displacement ($W_K$) of the total weight (body mass plus load). The limitation of the equation is that for downhill movement, the decrease in energy cost is overestimated (7). The problem may be two-fold. Negative work is essentially acceleration due to gravity. Gravity may be more efficient than muscular work, so applying the same constant may be incorrect. The second set of costs is eccentric work within the muscles and costs associated with maintaining stability – braking and maintaining lateral balance. It is difficult to isolate these factors based on the biomechanics of movement. For thermal modeling purposes, only the net or total energy costs are required. The approach used in this study was to derive a CF that could be subtracted from the value predicted by the PE for downhill movement to obtain the total energy requirement. Developing the CF is a pragmatic solution rather than an elegant, biomechanical solution. In keeping with the utilitarian aspect of our solution, only minimum input variables consistent with those required for the PE were used to derive the CF.

# METHODS

## VOLUNTEERS

Eight (8) volunteers, (6 males, 2 females) were recruited from the U.S. Army Soldier Biological and Chemical Command (SBCCOM) Headquarters Test Volunteer Detachment. The protocol was reviewed and approved by the USARIEM Human Use Review Committee, then forwarded for final review and approval by the Human Subject Research Review Board at Fort Detrick, MD. Prospective volunteers were informed of the purpose, procedures, and risks of the study and expressed their understanding by signing a statement of informed consent in compliance. Each volunteer was then cleared by a medical officer. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46.

## PRE-TESTING

Prior to traveling to the field test site, volunteers performed a continuous treadmill maximal oxygen uptake ($Vo_2max$) test (5). Height, weight, and age were recorded for each subject. To obtain fat-free body mass, subjects also underwent a low-dose dual energy X-ray absorptiometry (DEXA) measurement.

## FIELD TEST PLAN

All field testing was done at YTC in eastern Washington. To ensure that subjects were not exposed to a significant potential for heat strain, no test session was started if the Wet Bulb Globe Temperature index (WBGT) exceeded 78°F. YTC was selected as a test site based on information provided by the U.S. Army Topographic Engineering Center (TEC). YTC was selected after a data search of potential test locations at all U.S. military posts, and then potential test locations at YTC were visited and staked-out by TEC. The actual YTC test site were selected after several site visits by USARIEM personnel. For the initial study, we selected sites with grades of 4%, 8.6%, and 12%, plus the paved airstrip. Due to several problems at the 12% site, for this study we used a 10.2% grade site located just below the 8.6% grade site.

Each volunteer was to attempt 2 load carriage tests or exercise bouts (1 each, while carrying either no load or a load of 27.2 kg [60 lbs]) at walking speeds of 0.89 m/s and 1.12 m/s for each grade or slope condition. Those conditions were 3 uphill and 3 downhill slopes, plus the paved level condition (Table 1). The grades tested were 0% (level), 4%, 8.6%, and 10.2%. Due to the logistics of setting up and moving test sites, testing could be conducted at only 1 slope or grade per day, starting with the level site. If time constraints or equipment problems did not allow testing of all uphill and downhill loads and speeds, some uphill test runs would be eliminated.

Table 1. Description of test sites at Yakima Training Center (YTC)

| Site description, length (surface type) |
|---|
| Level, 0% grade (paved) and an adjacent track (dusty, hard earth) |
| 4% grade (gravel) |
| 8.6% grade (gravel) |
| 10.2% grade (gravel) |

Each 15-20 min exercise bout was separated by at least a 40 min rest period. All exercise bouts were paced at 1.12 $m \cdot s^{-1}$ (2.5 mph) and at 0.89 $m \cdot s^{-1}$ (2.0 mph). Initial testing began on the level site to enable subjects to become familiar with the test equipment. No more than 2 subjects participated during a given test bout.

Clothing for all exercise bouts consisted of the Battledress Uniform (BDU) and combat boots. The loads were carried in an issue (ALICE) field pack that weighs 2.8 kg with a frame. Total weight of clothing, pack, and oxygen monitor was approximately 9.4 kg.

The primary safety limit for terminating an exercise bout was reached if a subject sustained 90% of his/her individual's maximum heart rate for 5 min, as determined during $Vo_2$max testing. A testing bout could also have been terminated if the test staff deemed it necessary for any reason; or the volunteer felt, in any way, unable or unwilling to continue walking, or if a subject's core temperature had reached 38.5°C or WBGT was 26°C (78°F).

## Data Collection and Equipment

A Sensormedics 2900 (Yorba Linda, CA) metabolic measurement cart was used during the $Vo_2$max test. During the outdoor exercise bouts, COSMED $K4b^2$ (K4) portable oxygen consumption monitors (COSMED, Ltd., Rome, Italy) were used to collect data. Before exercising, each volunteer was fitted with a face mask attached to a hose directing expired gases to the K4. Heart rates were measured with a sports watch heart rate monitor (Polar® Heart Rate Monitor, Polar Electro, Inc., Woodbury, NY) to provide both data and safety monitoring. Core temperature was measured with a telemetric temperature pill that was swallowed (CorTemp™, Human Technologies, Inc., St. Petersberg, FL). The pill signal was displayed on a small hand-held receiver/data logger receiver (Personal Electronic Devices, Inc., Wellesley, MA). Oxygen uptake, heart rate, and core temperature were hand-recorded every minute during the exercise bouts. Subject weight, age and height were obtained at the time of $Vo_2$max testing. Body weights, with underwear, were obtained on each test day prior to testing. Subjects were also fitted with a foot motion monitoring device, but those results are reported separately (3).

Most test runs consisted of 2 subjects wearing the BDU uniform, and combat boots carrying an LC-1 (ALICE) frame and pack with either no load (zero) or the 27.2 kg (60 lbs) of steel shot in plastic bottles. The 0.89 or 1.12 $m \cdot s^{-1}$ pace was set with a measuring wheel (Master Measure MM50, Rolatape® Corporation, Spokane, WA) modified with a bicycle cylometer (Enduro 2 CC-ED200, Cateye Company, Ltd., Boulder, CO). Weather conditions were measured with a Wet-Bulb Global Temperature (WBGT) monitor (Metrosonics Hs-371 Heat Stress Monitor, Oconomowoc, WI, 53066).

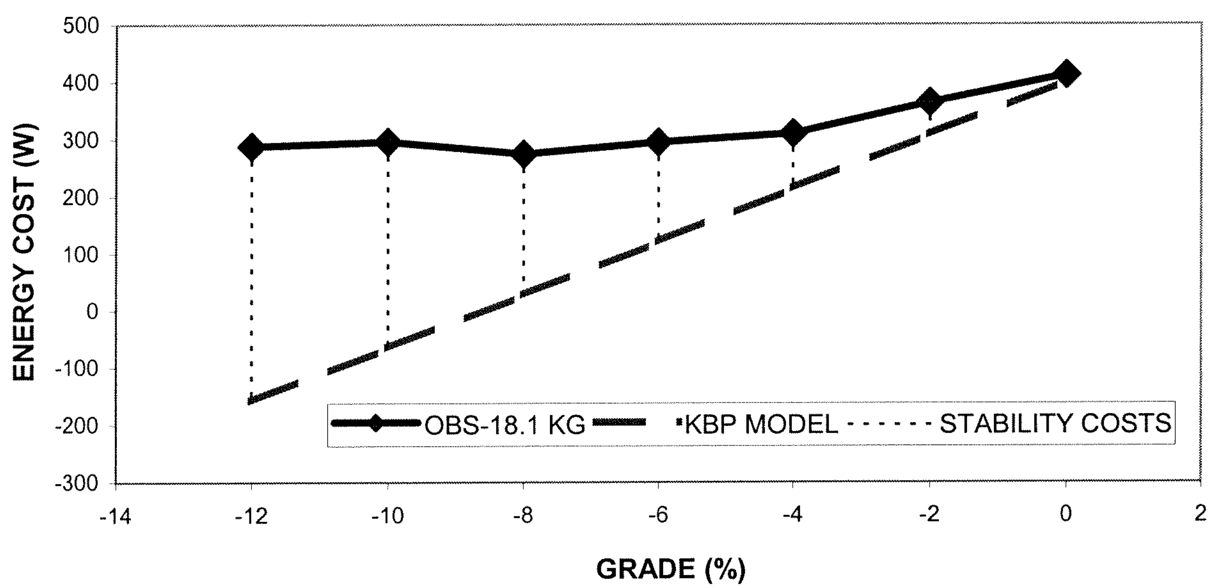
## FIELD TEST SCHEDULE

The basic test plan was to record physiological values for subjects as they walked at a steady pace on varying slopes while carrying a pack with a load of zero or 27.2 kg. Each subject would carry each load once per day both up and downhill at each speed (2x2x2), for a maximum of 20 min. Each 15-20 min load carry was considered a test run/bout. A maximum of 8 load carriage bouts per subject per day were planned. On the level site, subjects were to carry each load once on the paved runway. When time allowed at the level site, we attempted test runs on the adjacent hard-packed dirt track. Testing was conducted at only 1 site per day. Subjects were tested in alternating pairs, so each subject had at least a 40 min break between test runs. During most test runs, one subject carried the 27.2 kg load, and the other subject had the empty (no load) rucksack.

## MODELING

The difference between PE and observed values (N=16) from a prior laboratory study (8) of load carriage on treadmills run at a speed of 1.34 $m{\cdot}s^{-1}$ (Figure 2) was used to develop an estimate of the CF required to adjust PE for downhill movement. Initially, a linear regression was derived using a dummy variable for various combinations of grade (G) and total load (W+LD) and an estimate of speed (V) effect.

Figure 2. Energy costs predicted by Pandolf equation vs. observed costs for 18 kg load.



Total load includes nude weight (W) and load (LD). As the laboratory data were obtained for a constant speed, no treatment of the V variable could have an effect on the correlation, but the treatment of V did alter the constants in the derived regression equations. Although linear correlation coefficients were high ($R^2>0.9$), fit did not reflect the actual results. When the residuals for the linear regressions were plotted (Figure 3), the values approximated a parabola, thus indicating a predictable residual. The final CF incorporated the linear regression equation with an additional adjustment for the residuals. Only variables used in PE were used in CF. Figure 4 illustrates the fit between the adjusted PE and laboratory data. The final CF equation is:

$$CF = \eta \cdot [(G \cdot (W+L) \cdot V)/3.5 - ((W+L) \cdot (G+6)^2)/W) + (25-V^2)] \quad \text{(Equation 2)}$$

Figure 3. Residuals from linear regression for all 3 loads

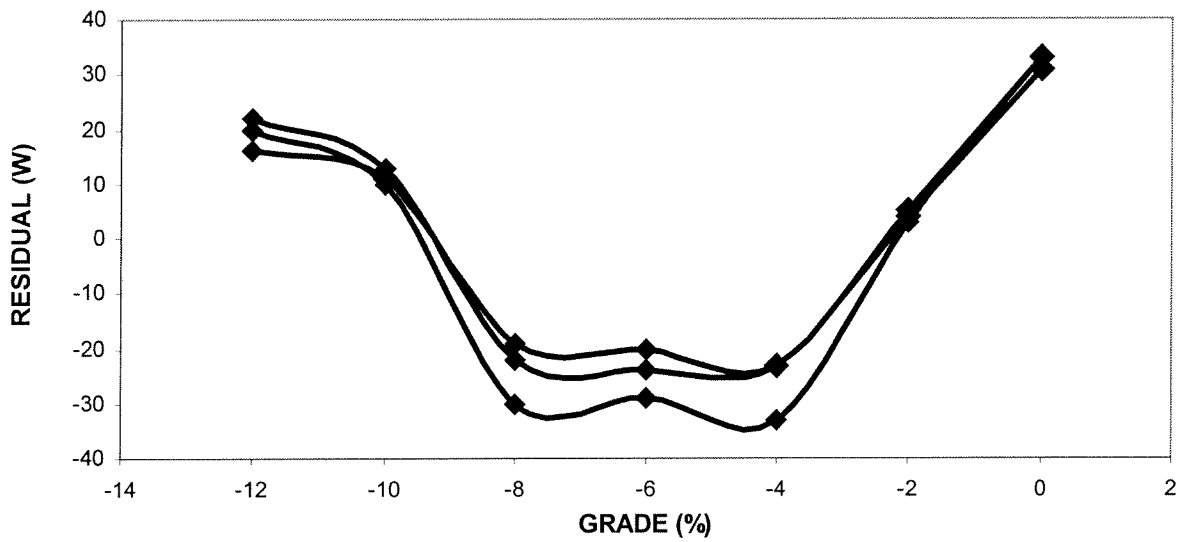
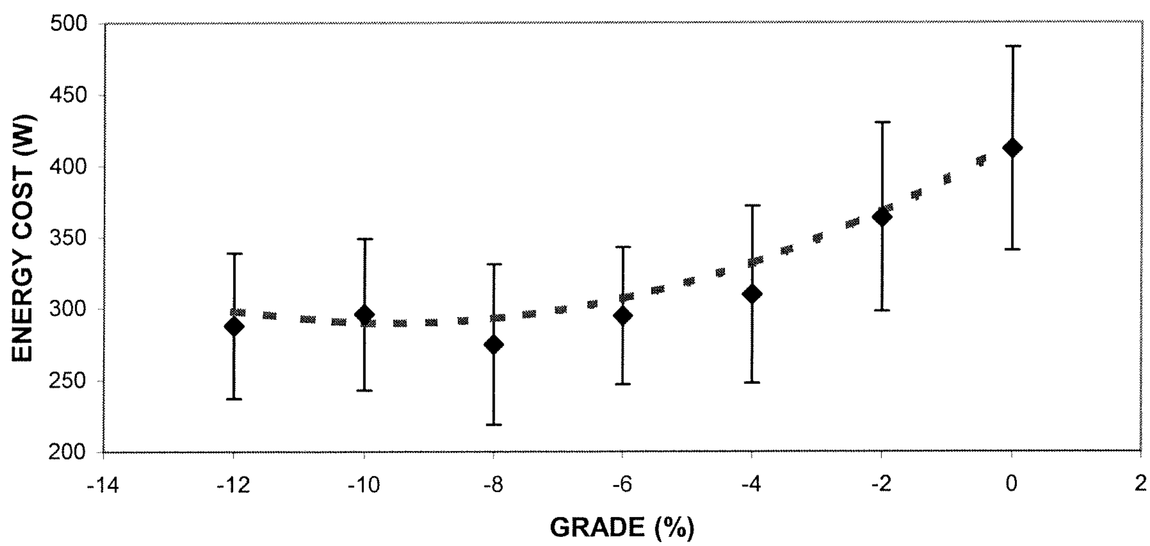



Figure 4. Model vs. observed values for energy cost of load carriage with 18 kg load



## DATA ANALYSIS

The Statistical Analysis System General Linear Model (SAS Institute, Cary, NC) was used to evaluate the fit between data set and the model. If no significant difference ($p > 0.05$) was found, the fit between data was considered acceptable.

## RESULTS

## SUBJECT POPULATION

Population variables (mean ± sd) for the 8 subjects were age (23 ± 3 yr), height (172 ± 9 cm), and weight 72.8 ± 9.2 kg). Maximum oxygen uptake ($Vo_2max$) was 51.4 ± 5.2 $mlO_2$/min/kg. Percent body fat was 21.2 ± 5.2 %. Table 2 lists individual values.

Table 2. Subject population dimensions

| Subject | Age yr | Gender | $Vo_2max$ $mlO_2$/kg/min | Weight kg | Height cm | Body Fat % |
|---|---|---|---|---|---|---|
| 1 | 22 | M | 47.9 | 83.9 | 180 | 12.2 |
| 2 | 27 | M | 47.5 | 83.7 | 175 | 16.8 |
| 3 | 26 | M | 55.0 | 75.3 | 180 | 24.5 |
| 4 | 21 | M | 60.5 | 70.6 | 170 | 19.9 |
| 5 | 21 | M | 54.0 | 75.4 | 170 | 21.2 |
| 6 | 23 | M | 53.9 | 57.3 | 152 | 20.3 |
| 7 | 20 | F | 46.3 | 72.9 | 175 | 28.8 |
| 8 | 21 | F | 46.1 | 63.5 | 173 | 25.8 |
| Mean | 23 | | 51.4 | 72.8 | 172 | 21.2 |
| s.d. | 3 | | 5.2 | 9.2 | 9 | 5.2 |

## DATA MATRIX

One test day was canceled due to high surface winds. One subject was removed due to a non-study related illness. Table 3 presents mean $VO_2$ (± 1 SD) values for all successful test runs. As in the 2000 field study, there was insufficient time to make all test runs; therefore, data collection was prioritized to obtain all of the downhill data, and in the time remaining, uphill data. For the 4 subjects that walked on the dusty, level surface with no load, the dirt-track values are divided by the paved surface values to derive an estimated terrain factor of 1.2. The conversion to whole body energy costs (W) from $VO_2$ values (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) was based on multiplying $VO_2$ by the nude body mass, then dividing by a conversion value of -2.87.

Table 3. Mean oxygen uptake values (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) by load

| Grade | Data – no load | | | Data – 27.2 kg load | | |
|---|---|---|---|---|---|---|
| | Mean | ±SD | N | Mean | ±SD | N |
| $0.89\ m \cdot s^{-1}$ | | | | | | |
| -10.2% | 267 | 6 | 8 | 372 | 84 | 8 |
| -8.6% | 201 | 52 | 7 | 267 | 42 | 8 |
| -4% | 143 | 47 | 7 | 221 | 74 | 7 |
| 0% | 176 | 65 | 5 | 277 | 40 | 7 |
| +4% | --- | --- | - | 417 | --- | 1 |
| +8.6% | 591 | 192 | 4 | 715 | 168 | 4 |
| +10.2% | --- | --- | - | --- | --- | - |
| $1.12\ m \cdot s^{-1}$ | | | | | | |
| -10.2% | 301 | 71 | 8 | 385 | 100 | 8 |
| -8.6% | 241 | 50 | 7 | 296 | 70 | 7 |
| -4% | 179 | 64 | 7 | 258 | 62 | 6 |
| 0% | 200 | 46 | 6 | 281 | 49 | 6 |
| +4% | 487 | --- | 1 | 492 | --- | 1 |
| +8.6% | 544 | 66 | 7 | 674 | 74 | 7 |
| +10.2% | 729 | --- | 1 | 836 | --- | 1 |

## MODELING RESULTS

The adjusted values, using the M=PE-CF format, fit well for walking at $1.12\ m \cdot s^{-1}$, but at $0.89\ m \cdot s^{-1}$, the values were underestimated. Figures 5-8 compare the mean energy costs (watts) to the values predicted with the adjusted estimate, PE-CF, for downhill and level walking and load carriage at both speeds and loads. Table 4 presents the predicted energy costs for the same data presented in Table 3. In an effort to indicate the variability of the predicted values, an SD derived from the range of predicted values is also included in Table 4.

Table 4. Energy costs predicted using the adjusted Pandolf equation

| Grade | Model – no load | | | Model – 27.2 kg load | | |
|---|---|---|---|---|---|---|
| | Mean | ±SD* | N | Mean | ±SD* | N |
| $0.89\ m{\cdot}s^{-1}$ | | | | | | |
| -10.2% | 230 | 24 | 8 | 331 | 12 | 8 |
| -8.6% | 177 | 21 | 7 | 266 | 13 | 8 |
| -4% | 164 | 20 | 7 | 240 | 10 | 7 |
| 0% | 166 | 20 | 5 | 247 | 9 | 7 |
| $1.12\ m{\cdot}s^{-1}$ | | | | | | |
| -10.2% | 291 | 32 | 8 | 417 | 20 | 8 |
| -8.6% | 233 | 23 | 7 | 332 | 19 | 7 |
| -4% | 203 | 25 | 7 | 297 | 17 | 6 |
| 0% | 202 | 23 | 6 | 297 | 13 | 6 |
| * SD based on variance of predicted values | | | | | | |

Figure 5. Predicted vs. observed energy costs for no load (0 kg) at $1.12\ m{\cdot}s^{-1}$

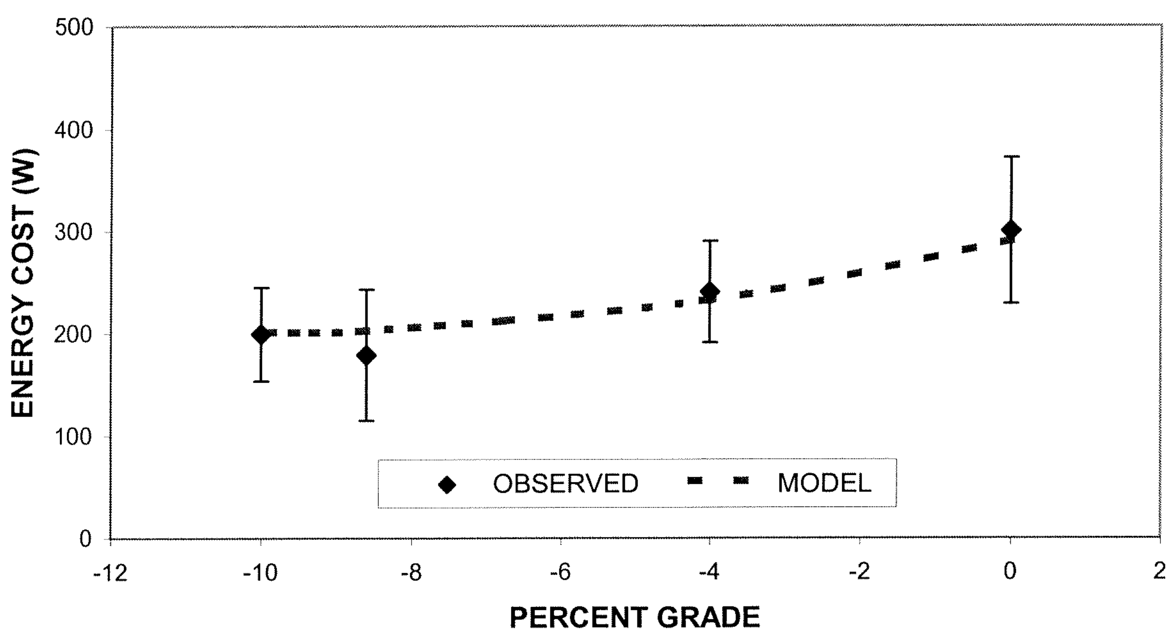


Figure 6. Predicted vs. observed energy costs for 27 kg load at 1.12 $m \cdot s^{-1}$

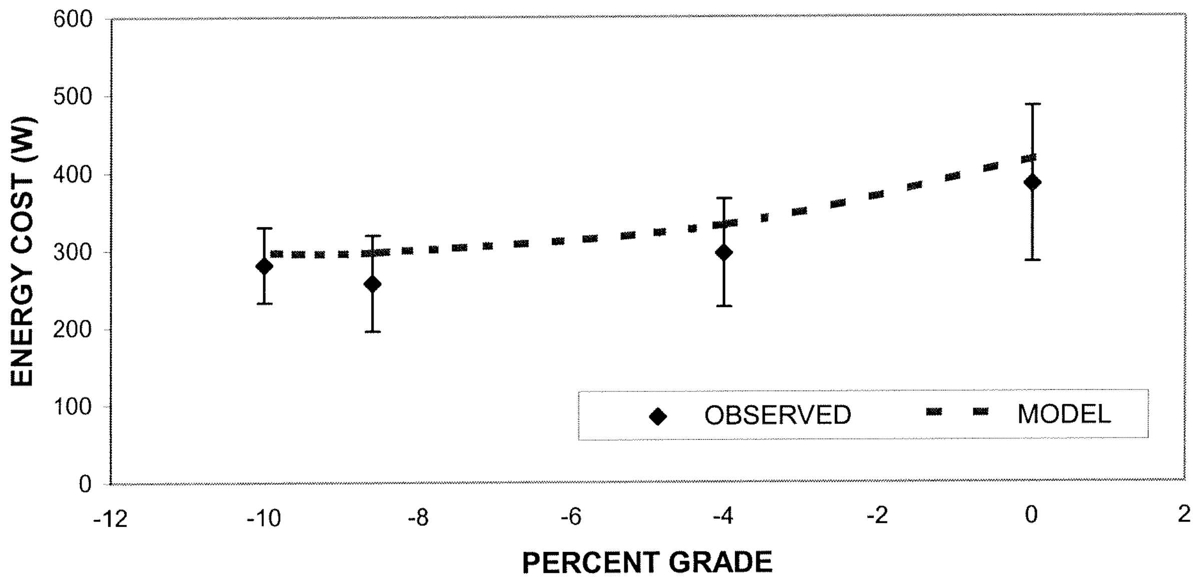



Figure 7. Predicted vs. observed energy costs for no load (0 kg) at 0.89 $m \cdot s^{-1}$

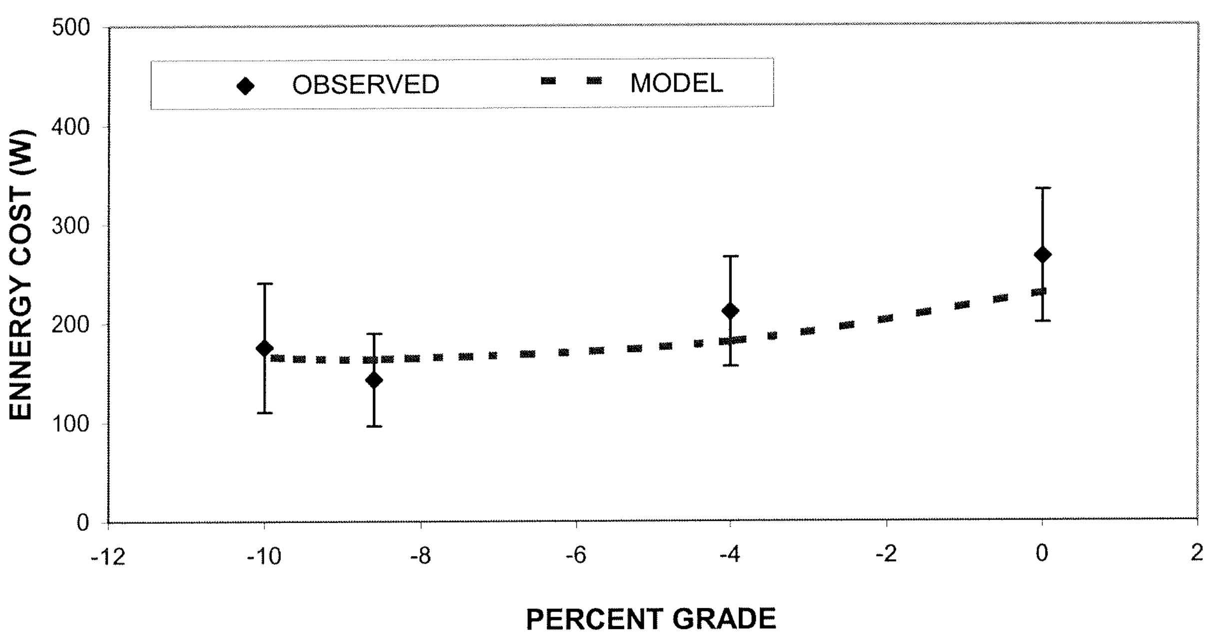
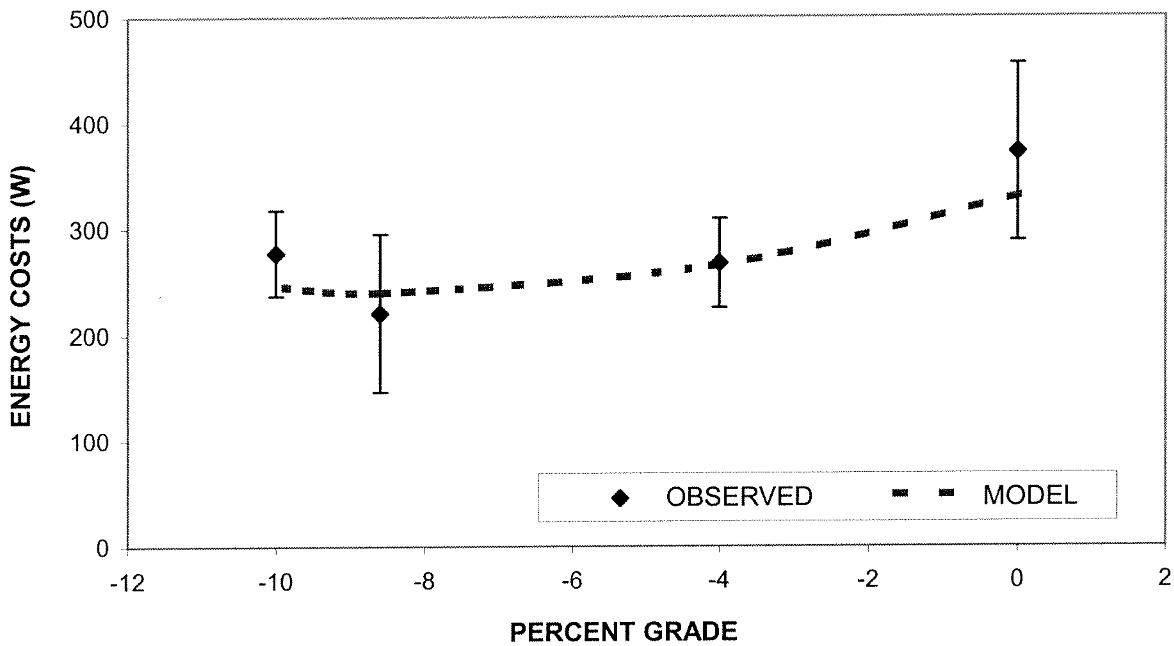


Figure 8. Predicted vs. observed energy costs for 27 kg load at 0.89 $m \cdot s^{-1}$




## DISCUSSION

The decision to develop an adjustment to the PE for downhill load carriage was predicated on the wide-spread acceptance of the PE and, more pragmatically, that choice eliminated the need to defend a new equation for uphill load carriage proposed in Santee et al. (8). Although the use of a residual equation to adjust the basic linear regression equation to derive the final CF was criticized in a program review (2), the method is exactly parallel to a hybrid application of neural net modeling, where residual values derived from the training set are used to adjust the variables in the initial predictive equation (J. Reifman – unpublished observations).

Another criticism of modeling in general is a failure to set confidence intervals for the predicted values. In Table 4, we presented the SD for the predictions. Those SD values do not represent the confidence limits of the model. Instead the SD values were presented to make the point that there is variability in the population and, therefore, in the predictions. It is not possible, however, to use the variability of the group to establish confidence intervals for the energy costs predicted for an individual.

One additional variable is the terrain factor ($\eta$). Although it is treated as a constant for our modeling, the original literature indicates more variability (10). The value for walking on roads was originally developed for a hard-packed surface (R.G. Soule, personal communications, October 12, 2000). Our field data for 4 subjects on the level but rutted hard-packed surface with heavy dust suggested a higher $\eta$ of 1.2 as opposed to the 1.1 value from Soule and Goldman (10). The combination of ruts and very thick dust (5-12 cm) makes any direct comparison questionable, but the data do provide an argument for modifying the value of $\eta$.

Minetti et al. (4) states that a walking speed of 1.0 ±0.3 $m{\cdot}s^{-1}$ was the most energy efficient speed for a level grade. Given that our modeling is based on a constant 1.34 $m{\cdot}s^{-1}$ database, there is a possibility of incorrectly estimating energy costs for other combinations of grade and walking speeds. During the study, there was one incident that did suggest that there was a lower limit to walking efficiency. On the 10.2% grade, with a 27.2 Kg load at 0.89 $m{\cdot}s^{-1}$, one taller test subject (180 cm) experienced spasms in his thigh muscles. Upon completing the exercise bout, the subject had trouble standing. This is an example of eccentric work, exacerbated by the short steps required to maintain the 0.89 $m{\cdot}s^{-1}$ pace. The increasing inefficiency with slower walking speeds could provide a rationale for the statistical results, which indicate that the predicted value fit the 1.12 $m{\cdot}s^{-1}$ data, but not the values observed for walking at 0.89 $m{\cdot}s^{-1}$.

The combined uncertainties of the reduced efficiency at lower walking speeds, and the possible need to modify the terrain factor provide sufficient reason to accept the fact that a CF derived from laboratory data may not adequately predict energy costs observed in the field. The obvious next steps are to develop new terrain factors and investigate the development of a non-linear adjustment for grade based on walking speed.

## CONCLUSIONS

A CF to adjust the widely accepted PE for downhill walking and load carriage was developed from treadmill data for slopes of -2%,-4%,-6%,-8%,-10% and -12%, while 16 subjects carried either no load, 9.1 kg, or 18.1 kg in a framed pack. The treadmill speed was 1.34 $m{\cdot}s^{-1}$. Data were collected in the field on gravel and paved roads with slopes of -4%, -8.6% and -10.2% at walking speeds of 0.89 $m{\cdot}s^{-1}$ and 1.12 $m{\cdot}s^{-1}$ and a load of 27.2 kg or no load (0 kg). There were no significant differences ($p > 0.05$) between the observed and predicted values for data collected at walking speeds of 1.12 $m{\cdot}s^{-1}$ indicating an adequate fit between observed and predicted data. However, for the 0.89 $m{\cdot}s^{-1}$ data, there were significant differences between the observed and predicted values. The better fit of the 1.12 $m{\cdot}s^{-1}$ data may be due to the smaller difference between that speed and the 1.34 $m{\cdot}s^{-1}$ speed used in the original laboratory study. Based on these results, further development of a CF for the PE may be required for walking speeds that are lower or higher than 1.34 $m{\cdot}s^{-1}$ that adjusts for changing efficiencies with varying slopes and walking speeds.

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